Synchrotron-Based Proton Driver

W. Chou

for the Proton Driver Synchrotron Study Group

October 9, 2003

Presentation to the Long Range Planning

Proton Driver Sub-Committee Town Meeting

Proton Driver Study Group

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Dave Wildman
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Two Simple Facts

- Every large HEP lab has an accelerator project but Fermilab:
  - CERN: LHC
  - KEK/JAERI: J-PARC (US$1.3B)
  - DESY: X-FEL (€700M)
  - GSI: Future ion facility (€700M)
  - SLAC: LCLS ($220M)
  - Fermilab: ?
- On the DOE HEP 20-year road map, among the 12 possible facility choices, proton driver is Fermilab's only logical choice for a secured future:
  - Two LHC upgrades: Non-U.S.
  - SNAP, proton decay: Non-accelerator
  - Super-B: SLAC
  - BTEV, (CKM): alone can't shoulder Fermilab's future
  - LC: Remote, insecure
  - Super-ν, off-axis ν, ν-factory, part of underground lab: All point to a proton driver

Outline

- A quick review of the proton driver history
- An 8-GeV proton driver synchrotron
  - Problems of the present Booster
  - Design considerations
  - Parameters, layout and lattice
  - Technical systems
- Improvement of the existing linac
  - Front end and tank 1 (10 MeV)
  - Low energy section (116 MeV)
  - High energy section (313 – 500 MeV)
- Cost estimate
- R&D plan
- Conclusions

http://www-bd.fnal.gov/pdriver/8GEV/

First Document on Proton Driver

September 1997

Fermi National Accelerator Laboratory

FERMILAB-TM-2021

A Development Plan for the Fermilab Proton Source

Edited by S.D. Holmes
For the Proton Source Summer Study Group

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

September 1997

First Meeting on Proton Driver with the Director

April 14, 1998 (w/ John Peoples)

PROTON DRIVER

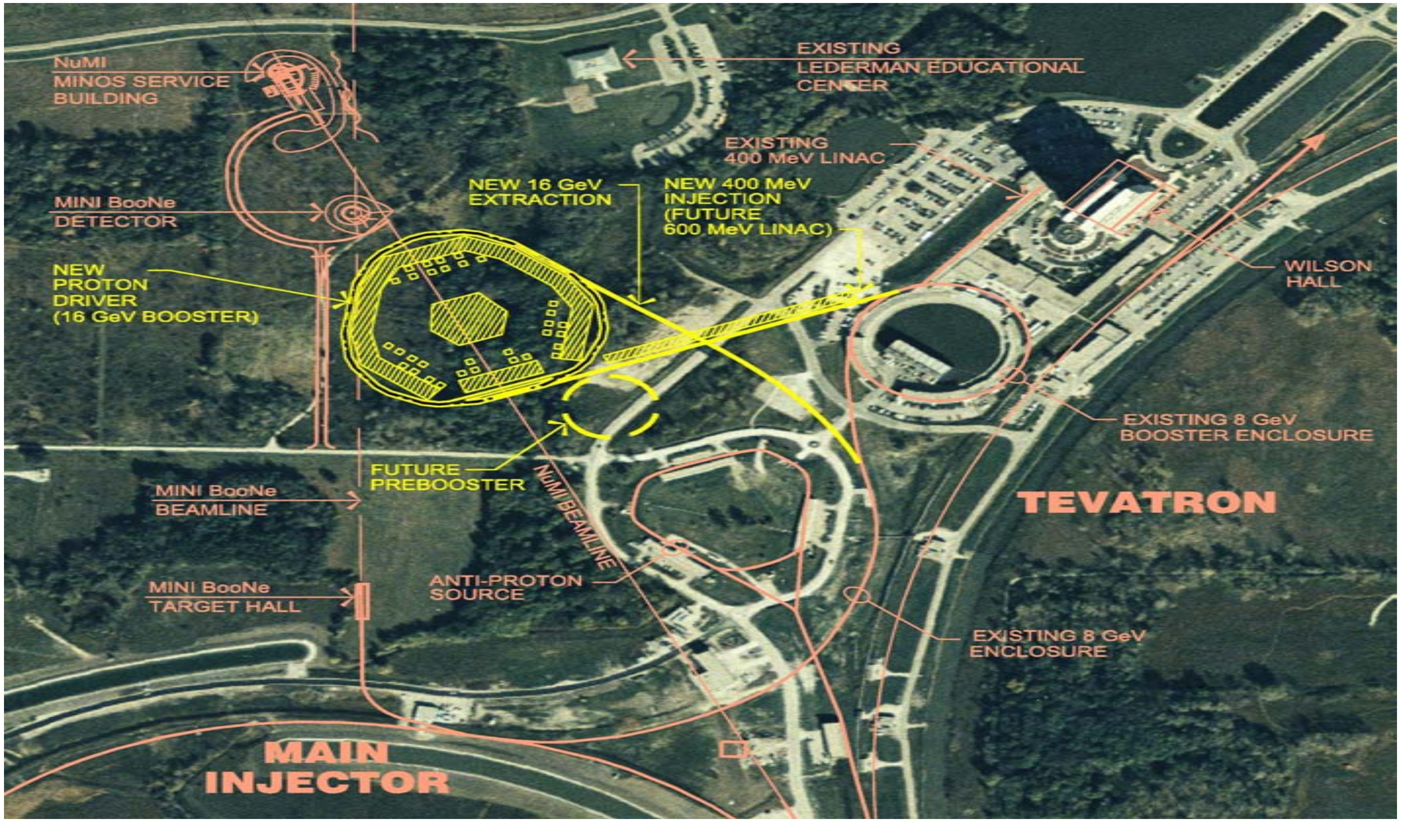
1. Primary requirements:
   - High intensity ptoton beams: 1×10^{14} ppp, 4 MW
   - High rep rate: 15 Hz
   - Short bunch length: $\sigma = 1$–2 ns at extraction
2. Design work:
   (a) Documents completed:
   - 1997 Summer Study Report
   - Two workshop reports
   - Proc. 1998 Muon Collider Collaboration Meeting

   (b) Document in preparation:
   - Feasibility Study (due July 1, 1998)

   (c) Document to start:
   - Conceptual Design Report (due July 2000)
3. Machine experiments:
   (a) Short bunch:
   - Bunch rotation at the Fermilab Booster
   - Beam near transition at the AGS

   (b) Inductive compensation of space charge effects:
   - Fermilab-LANL at the PSR
   - KEK at the PS
   - Fermilab-BNL at the AGS (being arranged)
4. Planned hardware R&D:
   (a) Prototype high power high gradient rf cavity
   (b) Prototype Inconel beam pipe
   (c) Prototype short large aperture magnet
   (d) Inductive insert
   (e) High current ion source
   (f) Prototype chopper

Proton Driver Study I: 16 GeV
(Fermilab-TM-2136, December 2000)



Snowmass 2001 WG 6 Report

August 10, 2001

Report of the Snowmass M6 Working Group on High Intensity Proton Sources*

Conveners: W. Chou (Fermilab) and J. Wei (BNL)
August 10, 2001

Charge to the group: Several present and future high-energy physics facilities are based on high intensity secondary particle beams produced by high intensity proton beams. The group is to perform a survey of the beam parameters of existing and planned multi-GeV high intensity proton sources and compare them with the requirements of high-energy physics users of secondary beams. The group should then identify areas of accelerator R&D needed to achieve the required performance. This should include simulations, engineering and possibly beam experiments. The level of effort and time scale should also be considered.

Outline

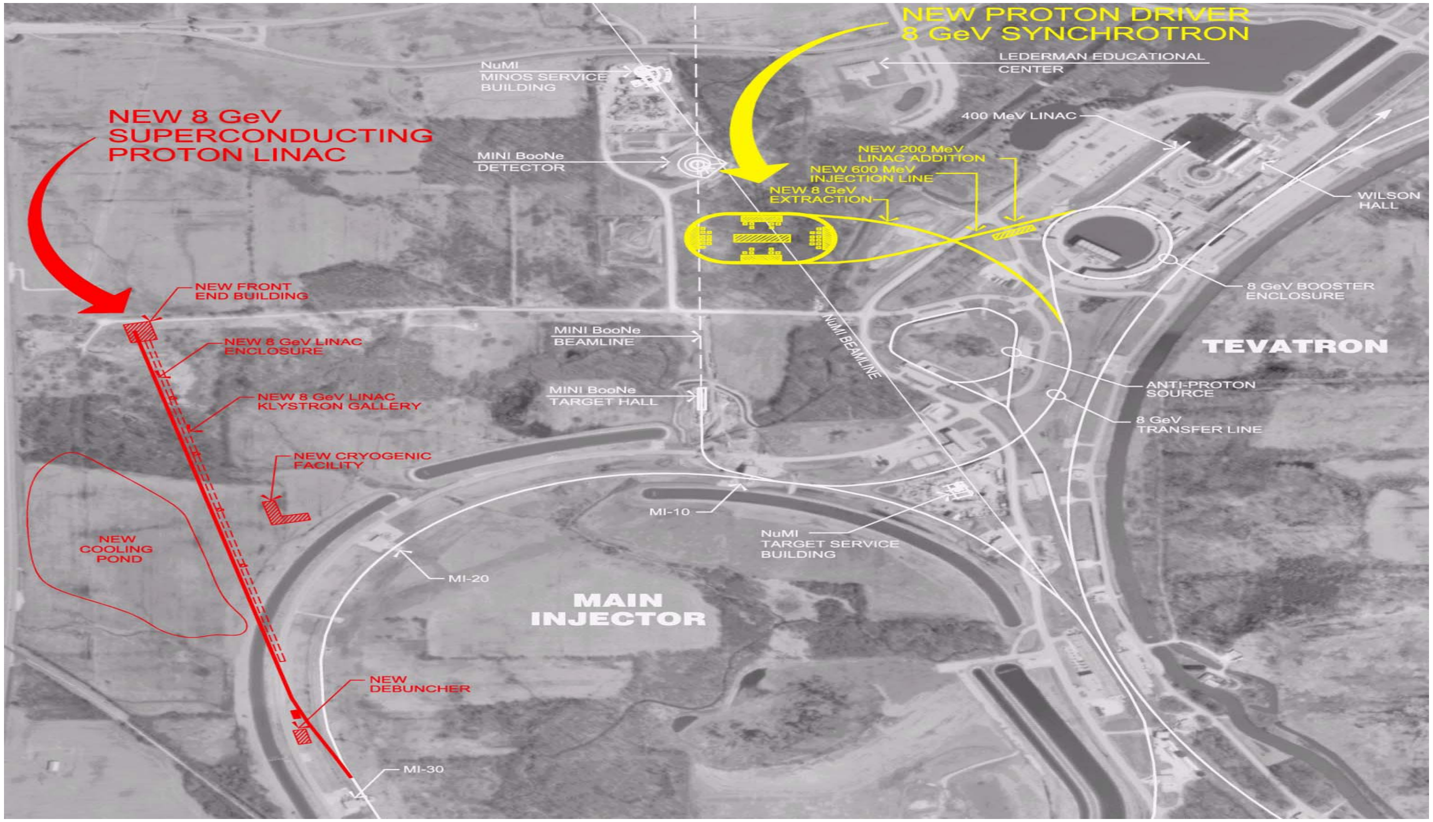
A New Charge from the Director

January 10, 2002

- The charge requested a design report consisting of three parts:
  - An 8-GeV synchrotron based proton driver
  - An 8-GeV linac based proton driver
  - A 2-MW upgrade of the Main Injector

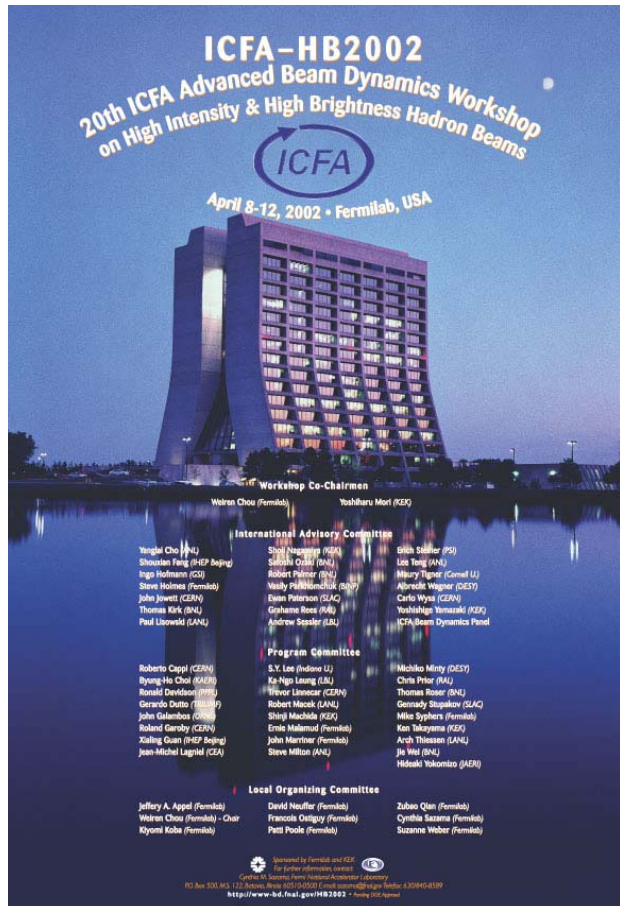
- The charge also requested the report be delivered to his office by May of 2002, i.e., in 5 months.

Proton Driver Study II: 8 GeV
(Fermilab-TM-2169, May 2002)



ICFA Workshop HB2002

April 2002



The Director is busy. Please wait …

Finally, after

- 6 years
- 3 charges from 2 directors
- 3 documentations by 3 teams
- 2 large workshops and 2 proceedings
- 3 reviews and 3 reports
- Countless meetings and discussions

Here comes …

A *New New* Charge from the Director

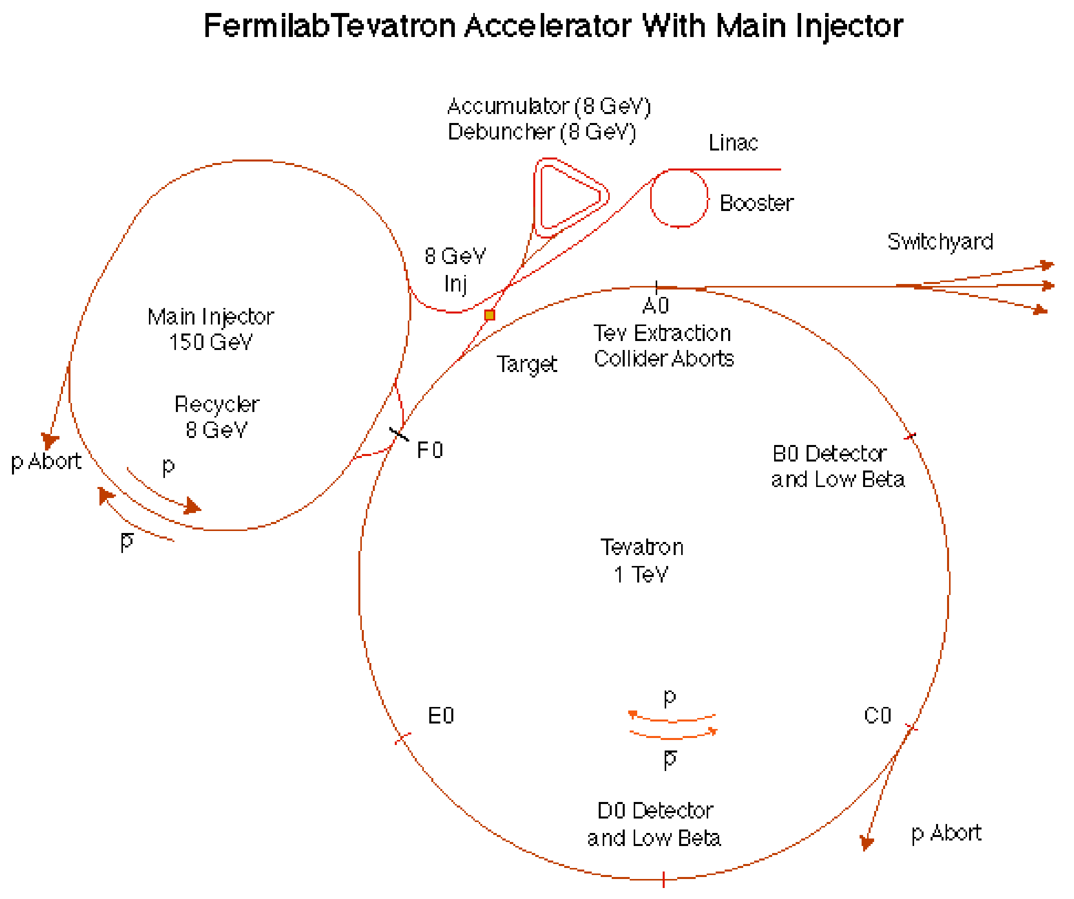
Early 2003

Charge to the Fermilab Long-range Planning Committee

The first recommendation of the 2001-2 HEPAP Subpanel on Long-Range Planning for U.S. High Energy Physics was "that the United States take steps to remain a world leader in the vital and exciting field of particle physics, through a broad program of research focused on the frontiers of matter, energy, space, and time." As the largest U.S. laboratory dedicated to High Energy Physics, Fermilab has a special responsibility to develop the research facilities needed to implement that recommendation.

The HEPAP Subpanel also recommended that the U.S. participate in the linear collider, wherever it is built in the world, and that the U.S. prepare to bid to host such a facility. Fermilab is working within the framework of the international and US steering groups to develop a global project, and to work out what it would take to host such a facility here. Finally, the HEPAP Subpanel argued persuasively that to address the range of compelling scientific issues the field needs a broad range of experimental strategies and techniques. Many of the experiments that exist as possibilities on the roadmap would be most easily done at Fermilab.

Fermilab Accelerator Complex



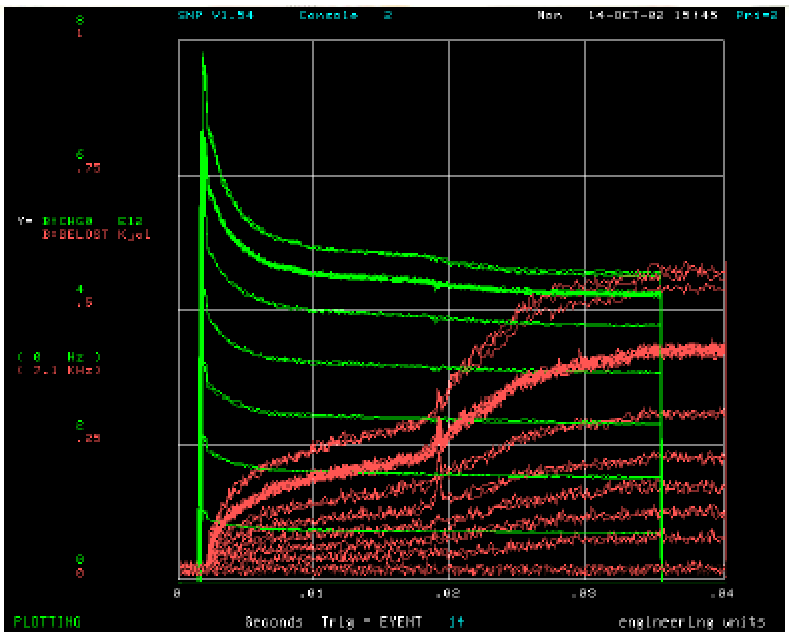
Booster is the Bottleneck

- The Booster is a 30 years old machine and has never been upgraded.
- The 400-MeV Linac can provide 25e12 particles per Booster cycle.
- The 120-GeV Main Injector can accept 25e12 protons per Booster cycle with modest upgrade.
- However, the 8-GeV Booster can only deliver 5e12 particles per cycle.

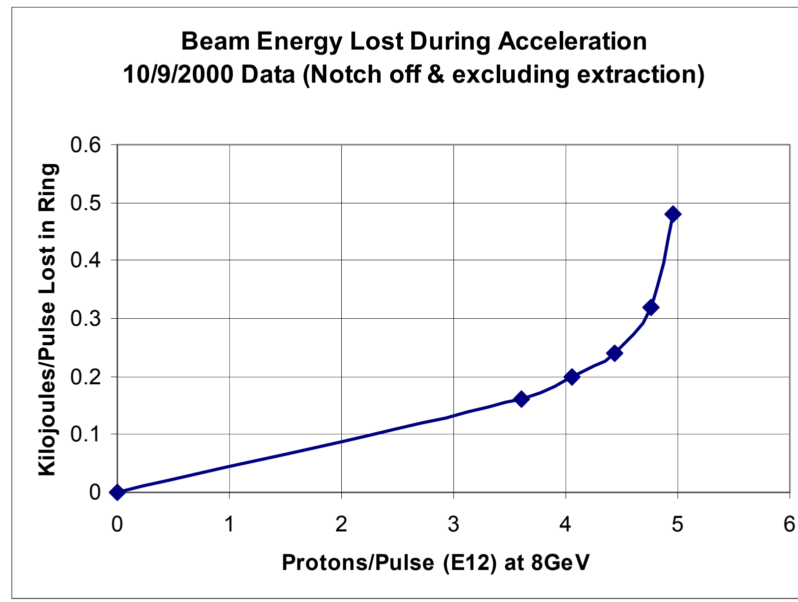
Booster Tunnel

Booster Beam Loss

(courtesy R. Webber)



For 0, 2, 4, 6, 8, 10, 12, 14 Injected Turns



Problems of the Booster

- Three fundamental problems:
  - Magnet aperture too small (vertical 1.6/2.2 in., horizontal good field region ~ 2.4 in.)
  - Linac too close to the ring
  - Tunnel not deep enough (13.5 ft.; and worse, buildings on top)

  Any change of these would mean a new machine.

- Other problems:
  - Transition crossing (γ_t = 5.45)
  - Large beta- and dispersion functions (33.7/20.5 m, 3.2 m)
  - Small RF cavity aperture (2-1/4 in.)
  - RF cavity in dispersive region
  - No RF shield inside the magnet
  - Limited orbit correction capability

  Some of these are being changed as part of Booster upgrade.

8-GeV Proton Driver Synchrotron
Design Considerations

- Large magnet aperture (good field region 4 in x 6 in)
- Space reserved between the linac and ring for future linac energy upgrade
- The tunnel is twice as deep (27 ft.; no buildings on top)
- Transition free (γ_t = 13.8)
- Small beta- and dispersion functions (15.1/20.3 m, 2.5 m)
- RF cavity aperture 5 in.
- RF cavity in dispersion-free straight sections
- Thin metallic beam pipe reinforced by spiral ribs
- AC correctors with sufficient strength throughout the cycle
- Phase space painting during multi-turn injection
- Dual harmonic magnet power supply for 25% RF power reduction
- Two-stage collimator system for keeping uncontrolled beam loss below 1 W/m

Scope of the Design

- A new 8-GeV rapid cycling synchrotron replacing the Booster
  - Beam intensity increased by a factor of 5
  - Beam power increased by a factor of 15
- A new linac extension of 200 MeV (to bring the linac energy to 600 MeV)
- A modest improvement of the existing H^- source and 400 MeV linac
- New 600 MeV and 8 GeV transport lines
- New enclosures

Parameters

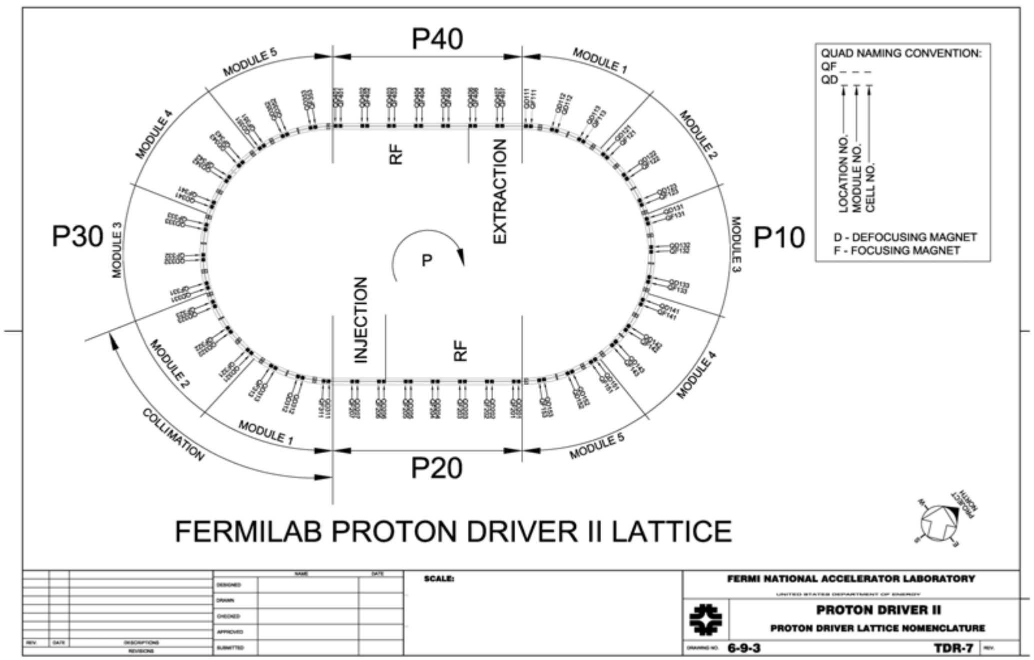
Parameters	Present Proton Source	Proton Driver (PD2)
Linac (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (μs)	25	90
H^- per pulse	6.3×10^{12}	2.8×10^{13}
Average beam current (μA)	15	67
Beam power (kW)	6	40
Booster (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	6×10^{10}	3×10^{11}
Number of bunches	84	84
Protons per cycle	5×10^{12}	2.5×10^{13}
Protons per hour	9×10^{16} (@ 5 Hz)	1.35×10^{18}
Normalized transverse emittance (mm-mrad)	15π	40π
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (μA)	12	60
Beam power (MW)	0.033 (@ 5 Hz)	0.5

Notes to the Beam Power

- Such a PD would bring the MI beam power to 2 MW. So the total beam power (PD + MI) would reach 2.5 MW. This should be compared with the present MI beam power of 0.3 MW.

- Besides, the proton driver itself can be increased from 0.5 to 2 MW with a “modest” linac energy upgrade from 600 MeV to 1.9 GeV (space reserved between the linac and the new ring).

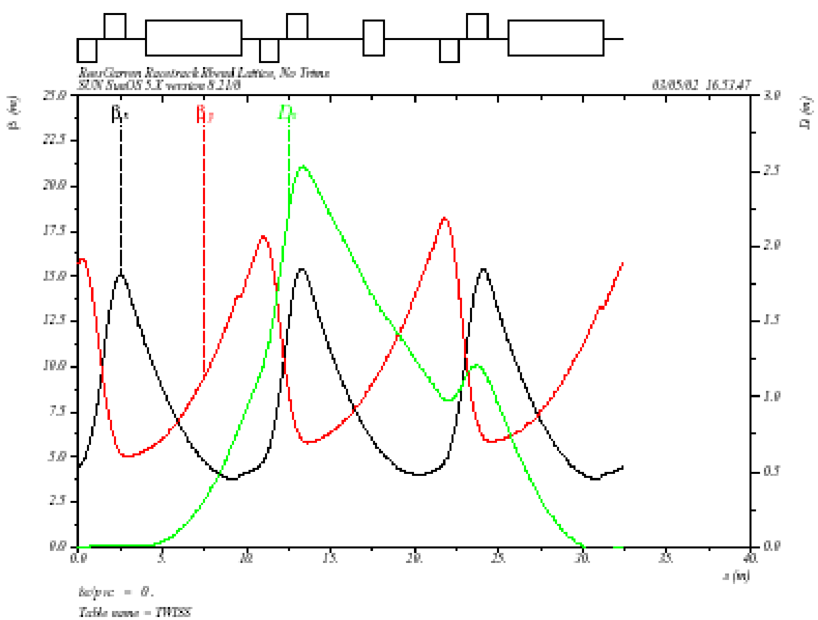
Layout



- Racetrack shape
- 2 arcs, 2 straights
- Each arc with 5 modules
- Each module with 3 doublet cells
- Straight sections for injection, extraction and RF
- Plenty space for diagnostics in the arcs and straights

Lattice

Arc module

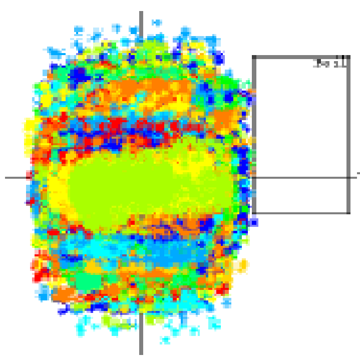


- Transition-free
- Dispersion-free straight sections
- Arc module: doublet 3-cell structure with a short dipole in the mid-cell
- Phase advance per module 0.8 and 0.6, respectively, in h- and v-plane

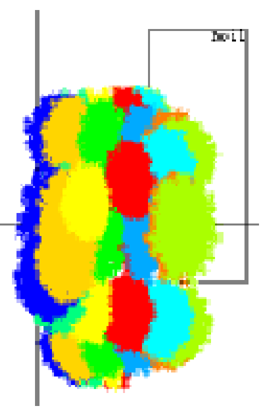
Space Charge

x-y plot of the multi-turn injection beam cross section

with s.c.



without s.c.



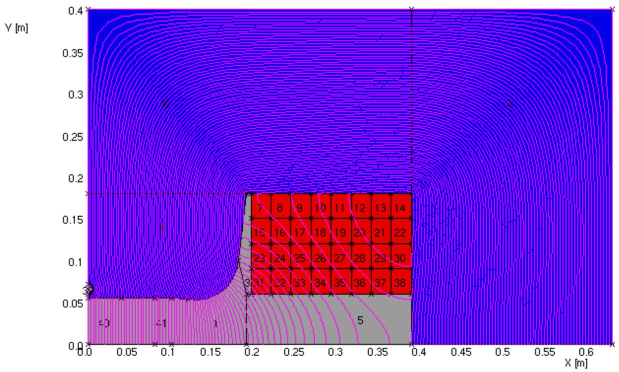
- Space charge is a main concern for low energy high intensity proton machines
- Numerical simulations by using three codes:
  - ESME (J. MacLachlan, FNAL)
  - ORBIT (J. Holmes, ORNL)
  - Track2D (C. Prior, RAL)

RF

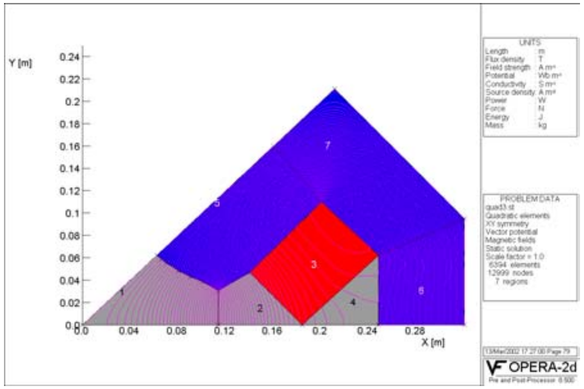
- Booster RF will be reused with modifications:
  - To increase the aperture from 2-1/4 in. to 5 in.
  - To increase the gap voltage from 55 kV to 66 kV.
- Two (out of 18) cavities have been modified and will be installed during summer shutdown.

Magnet

Dipole

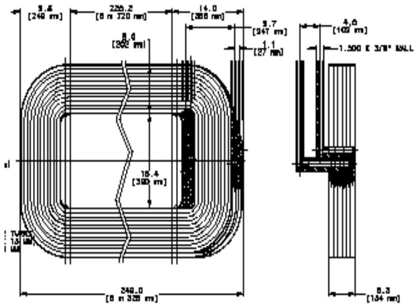


Quadrupole



Stranded conductors

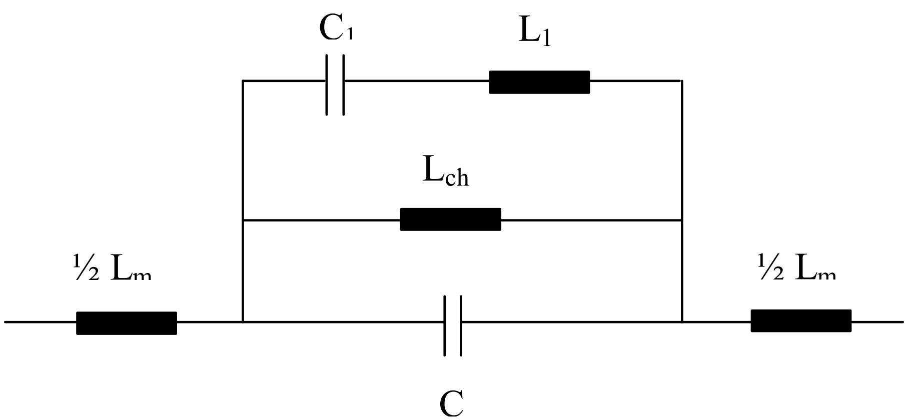
Standard conductors with parallel connection



Dual Harmonic Power Supply

DC 15 Hz 30 Hz

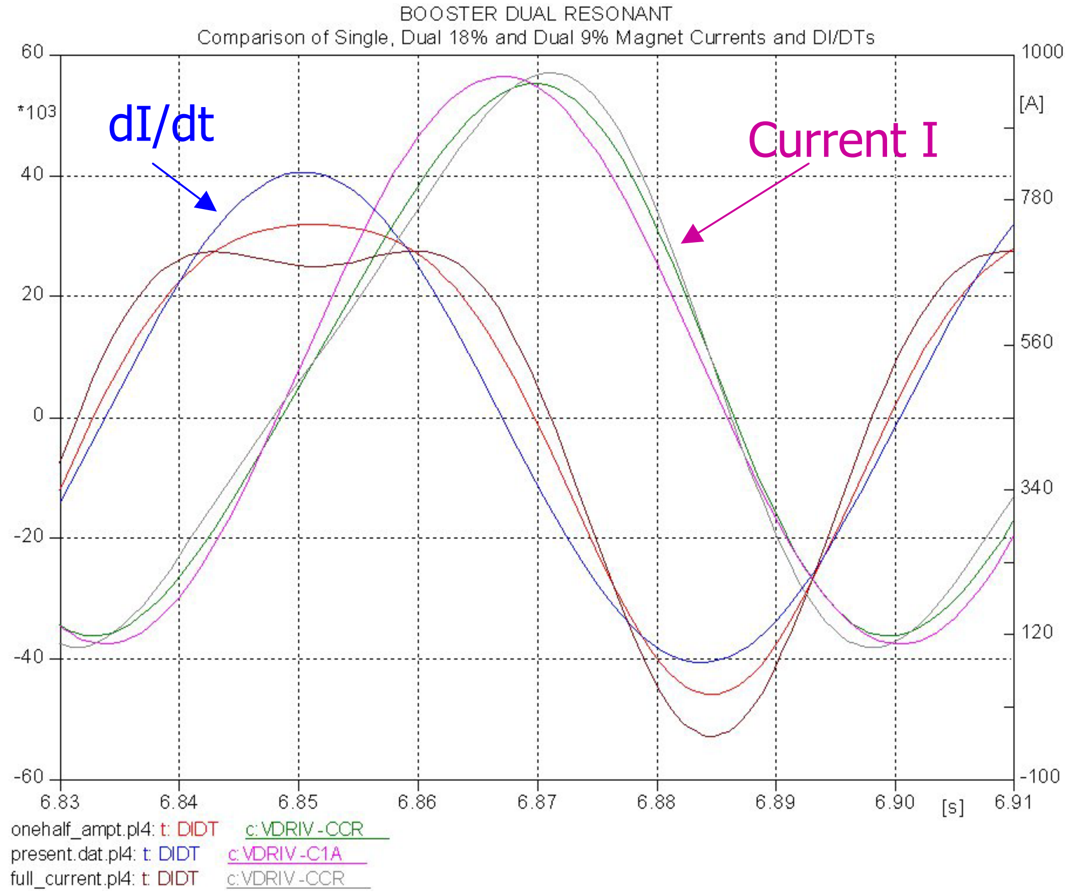
$$B(t) = B_0 - B_1 \cos(2\pi f t) + B_2 \sin(4\pi f t)$$



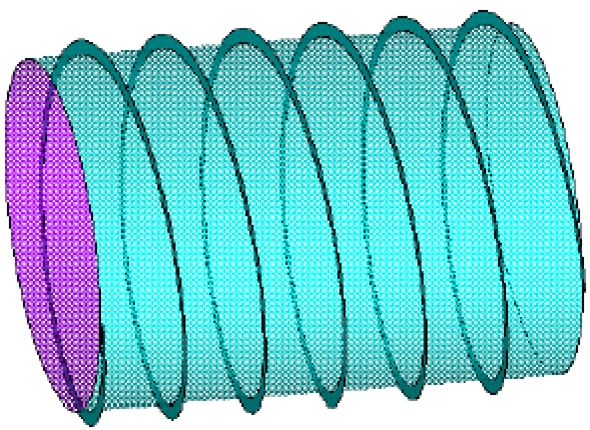
- B_2 = 12.5% B_1
- Peak RF power (∝ dI/dt) reduced by 25%
- Test at E4R using Booster power supply

Dual Harmonic Current and dI/dt

(3 cases: dual 0%, 9%, 18%)



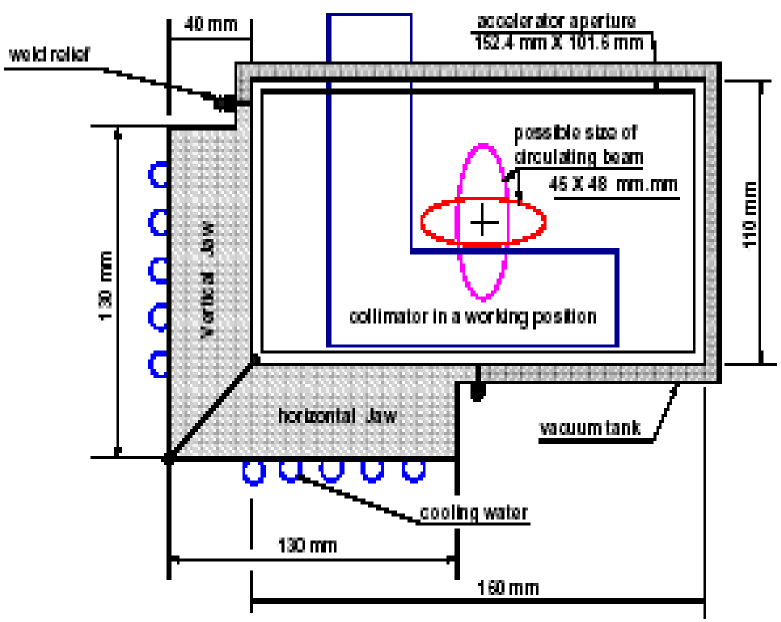
Beam Pipe



- New design: thin metallic pipe reinforced by spiral ribs
- Aperture: 4 in x 6 in oval
- Material: Inconel 718
- Wall thickness: 8 mils (0.2 mm)
- Spiral ribs: rectangular cross-section, width 28 mils, height 18 mils, 10 layers (total height 0.18 inch)
- Welding technique: laser deposition

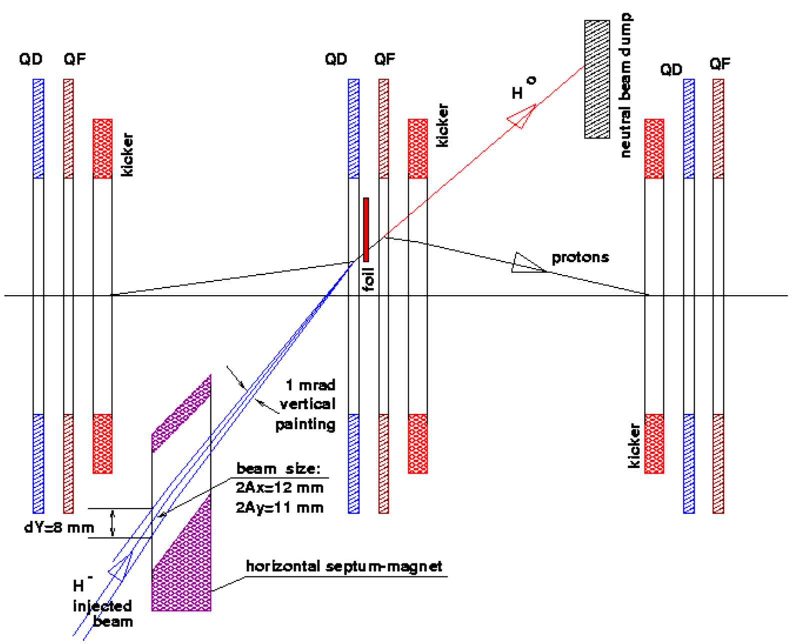
Collimator

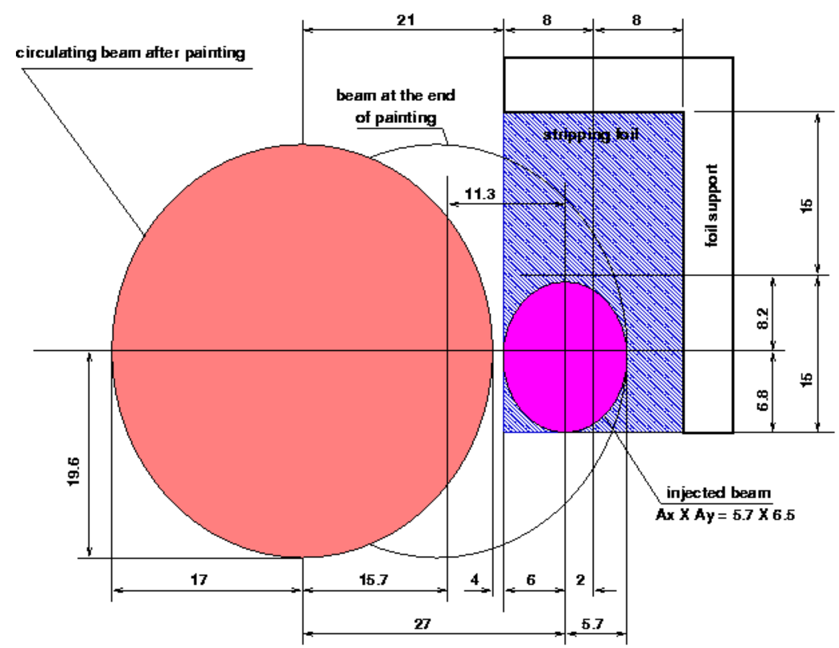
Collimator cross section



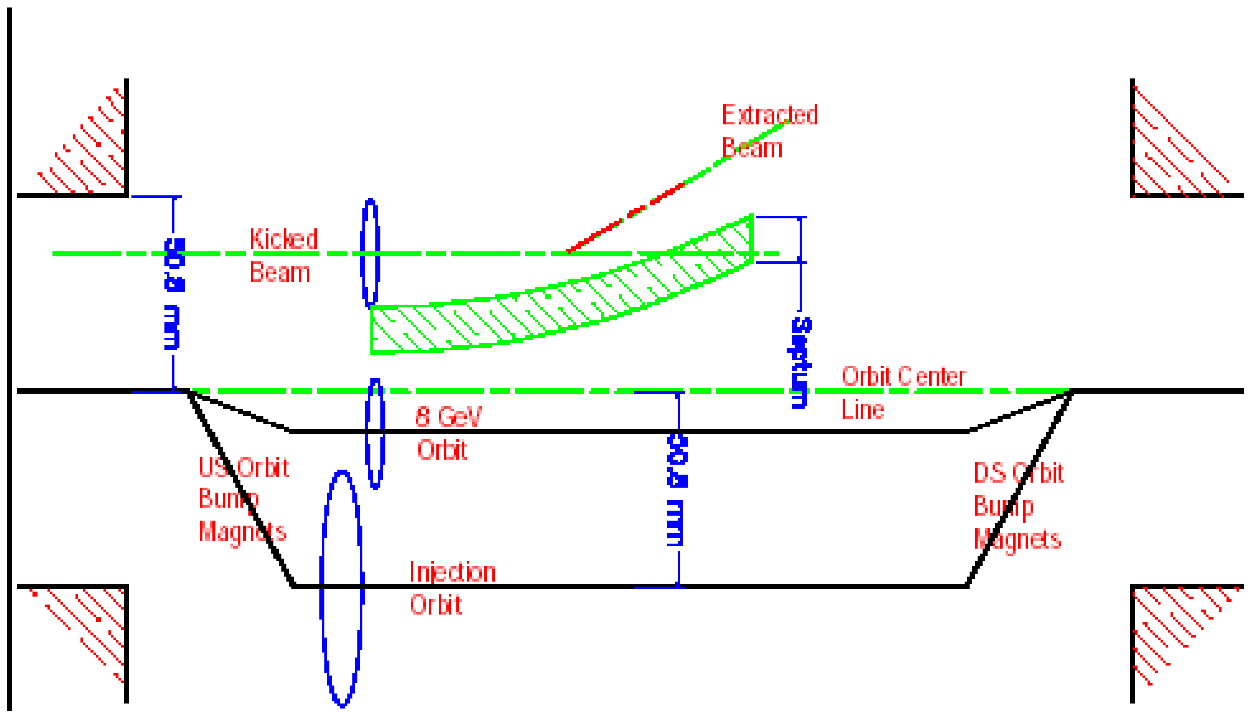
- To allow hands-on maintenance, the uncontrolled beam loss must be kept below 1 W/m
- A 2-stage collimator system will collect more than 90% of the lost particles (controlled beam loss)
- The collimator area will be "hot," but most of the tunnel will be "cool"

Injection with Painting



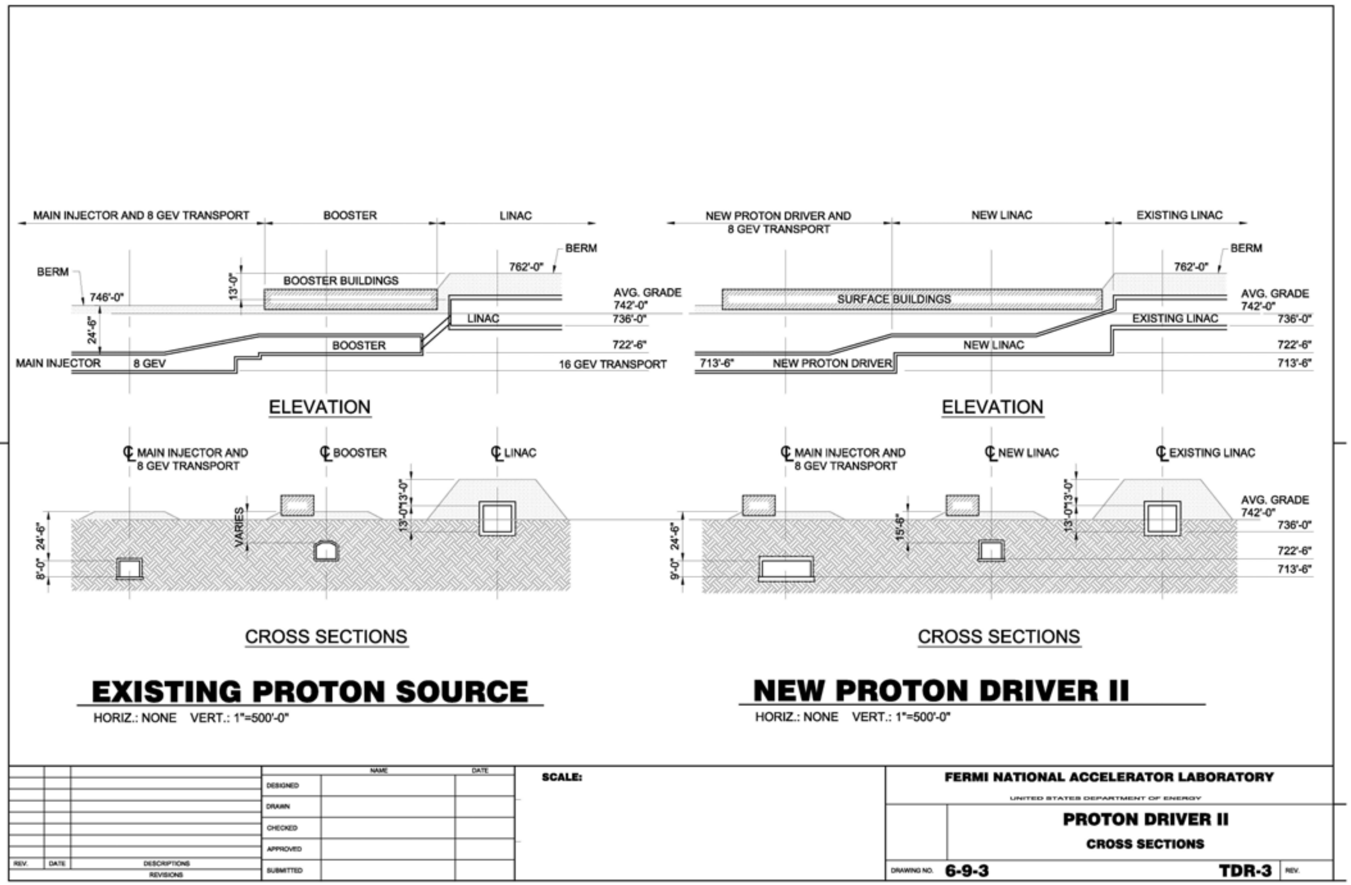


Extraction



Extracted
Beam
Kicked
Beam
50.8 mm
Septum
Orbit Center
Line
8 GeV
Orbit
US Orbit
Bump
Magnets
DS Orbit
Bump
Magnets
50.8 mm
Injection
Orbit

Tunnel Elevation



Improvement of the Existing Linac

- Linac improvement:

  This is the "common denominator" of the two proton driver options (linear or circular) and can go ahead regardless which option would be chosen.

- There are three choices: (choose as many as you wish)

  (1) New 201 MHz front end & Tank 1 (10 MeV)

  (2) New 402 MHz low energy section (116 MeV)

  (3) New 805 MHz sc high energy section (313 - 500 MeV, replacing CCL station no. 6 and 7)

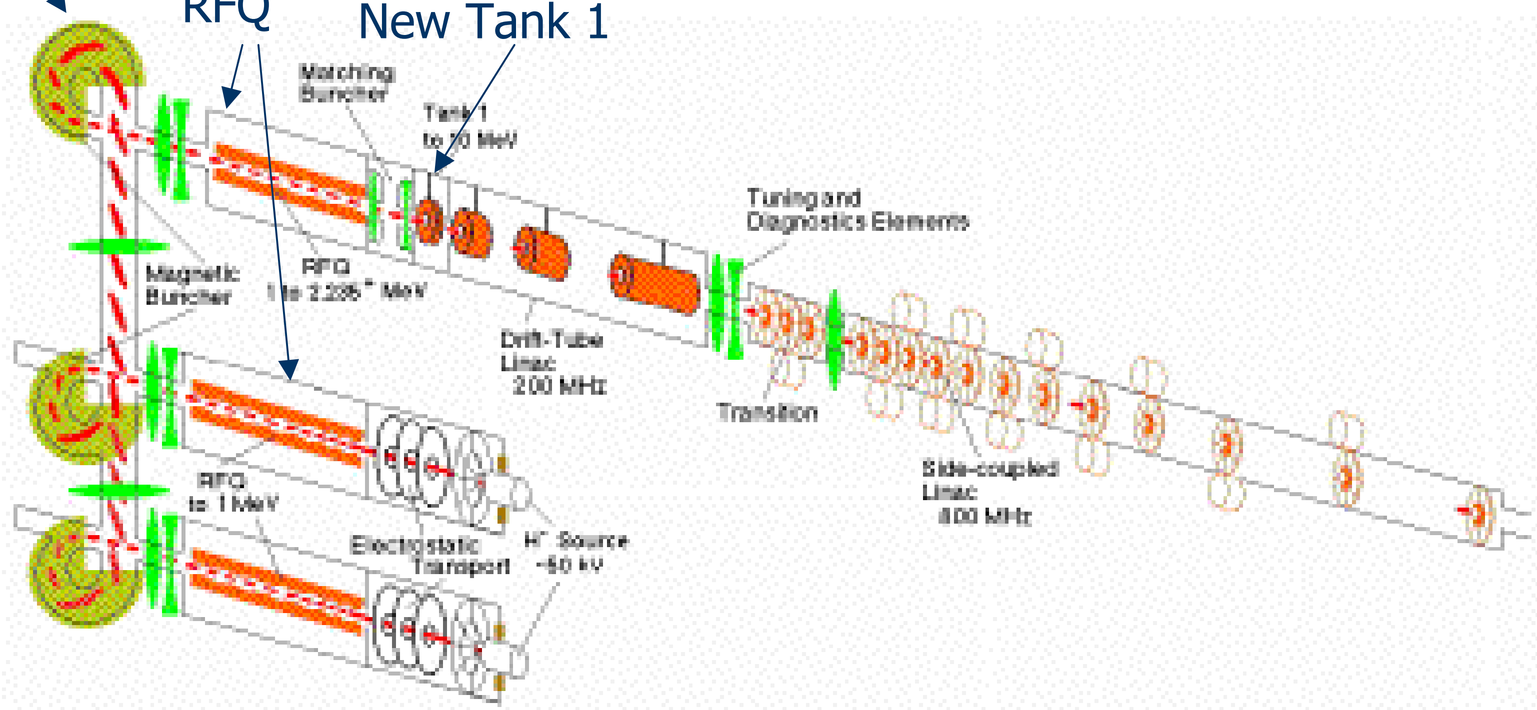
(1) Linac New Front End & Tank 1

(10 MeV)

Alpha magnet

RFQ

New Tank 1



(2) New 402 MHz Low Energy Section
(116 MeV)

				DTL			CCL	
	RFQ	Tank 1	Tank 2	Tank 3	Tank 4	Match Section	Mod 1	Mod 2
MeV	0.035	3	13.4	32.9	51.6	70.3	70.3	93.3
MeV	3	13.4	32.9	51.6	70.3	70.3	93.3	116.5
MeV	2.965	10.4	19.5	18.7	18.7	0	23	23.2
mA	70	55	55	55	55	50	50	50
MHz	402.5	402.5	402.5	402.5	402.5	805	805	805
usec	90	90	90	90	90	90	90	90
usec	130	130	130	130	130	125	125	125
Hz	15	15	15	15	15	15	15	15
	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
MV/m		2.4 to 4.6	4.6	4.6	4.6	7.5 to 7.35	8	8
m		4.5	6	6.1	6.2	3.25	4.8	4.9
MW		1	1.75	2	2		5.4	5.4
MW		0.63	1.07	1.02	1.02		1.38	1.39
MW		2.5	3.8	4	4		8.5	8.5

(2) New 402 MHz Low Energy Section (cont…)

The cost estimate of this 402 MHz low-energy system in 2002 dollars is as follows (in K$):

Components, including the RFQ, RGDTL, DTL, matching section, CCL, DTL rf systems, matching section rf systems, beam diagnostics, and the control systems	24,649
Installation and commissioning	2,500
Building modifications	500
TOTAL (K$)	27,649

(3) New 805 MHz SC High Energy Section
(313 – 500 MeV)

- Retain the existing CCL stations No. 1-5 for accelerating the beam to 313.6 MeV.
- Replace the last two CCL stations No. 6-7 by SNS-type β=0.81 sc cavity for an energy upgrade to 500 MeV.
- The requires a "real estate" gradient of 9.5 MV/m in a 19.5 m long space, which is feasible.
  - The peak field is 35 MV/m, already achieved by the SNS
  - The fill factor is 0.63, which will require some changes in the SNS design (using quadrupole doublet, replacing SNS input coupler by TESLA type)

Cost Estimate – Proton Driver

1	**Technical Systems**			98,986
1.1	8 GeV Synchrotron		78,997	
1.2	Linac Improvements and Upgrade		17,500	
1.3	600 MeV Transport Line		900	
1.4	8 GeV Transport Line		1,589	
2	**Civil Construction**			37,152
2.1	8 GeV Synchrotron		17,500	
2.2	Linac extension		2,500	
2.3	600 MeV Transport Line		1,800	
2.4	8 GeV Transport Line		2,200	
2.5	Site work		4,800	
2.6	Subcontractors OH&P		5,760	
2.8	Environmental controls and permits		2,592	
	Total Direct Cost			**136,138**
	EDIA (15%)			20,421
	Lab Project Overhead (13%)			20,353
	Contingency (30%)			53,073
	Total Estimated Cost (TEC) ($k)			**229,985**
	(in FY02 dollars)			

Notes to the Cost Estimate

- A fair comparison between different design options (e.g., linear *vs.* circular) is the total direct cost, which is $136M for the synchrotron. The TEC depends on the cost model.

- Our cost model (EDIA, overhead, contingency) is the same as that in the BNL proton driver report. The BNL's TEC is $390M for 1 MW beam power, whereas Fermilab's is $230M for a PD and $36M for an MI upgrade, a total of $266M for 2.5 MW.

Cost Estimate – Linac Improvement

New 200 MHz front end & Tank 1 (10 MeV)	$4M
New 402 MHz low energy section (116 MeV)	$27.6M (incl. $4M)
New 805 MHz sc high energy section (313 – 500 MeV)	(TBD)

R&D Plan

- One important feature of the Proton driver synchrotron R&D is that it can help and is helping improve the Booster performance.
- The three major Booster projects during this shutdown are to large extent spin-offs of the proton driver study.
  - Collimators
  - Doglegs
  - RF cavity modification
- Proton Driver R&D list:
  - Space charge study
  - Inductive inserts
  - Dual harmonic power supply test in E4R
  - Magnet field measurement in E4R
  - Laser chopping
  - AC sc magnet development
  - Beam pipe prototyping

RF Cavity Modification

(courtesy J. Reid)

- Booster RF will be reused with modifications:
  - To increase the aperture from 2-1/4 in. to 5 in.
  - To increase the gap voltage from 55 kV to 66 kV.
- Two (out of 18) cavities have been modified and are being installed during this shutdown.

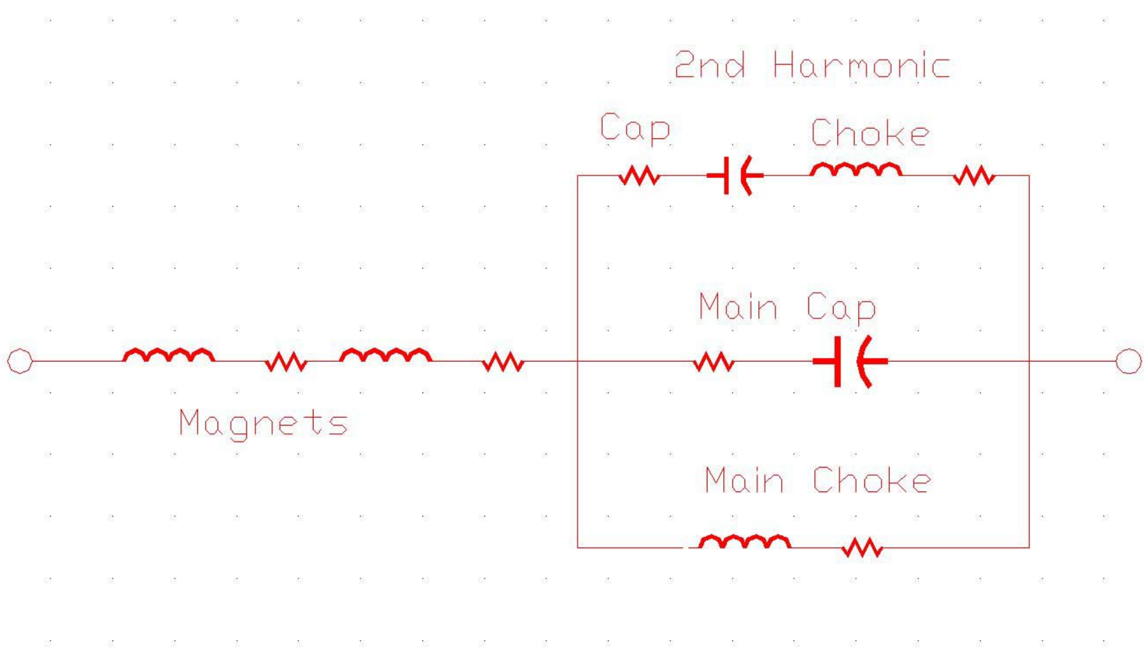
Space Charge Study

- Code development
  - ESME (P. Lucas, J. MacLachlan)
  - ORBIT (F. Ostiguy, L. Michelotti, W. Chou)
  - Synergia (P. Spentzouris, J. Amundson)
- Weekly Booster space charge study meeting

Inductive Insert
(courtesy D. Wildman and J. Lackey)

- For compensating space charge
- Test will be done in the Booster
  - Two modules have been tested, but inductance too low
  - A total of seven modules have been made and will be installed

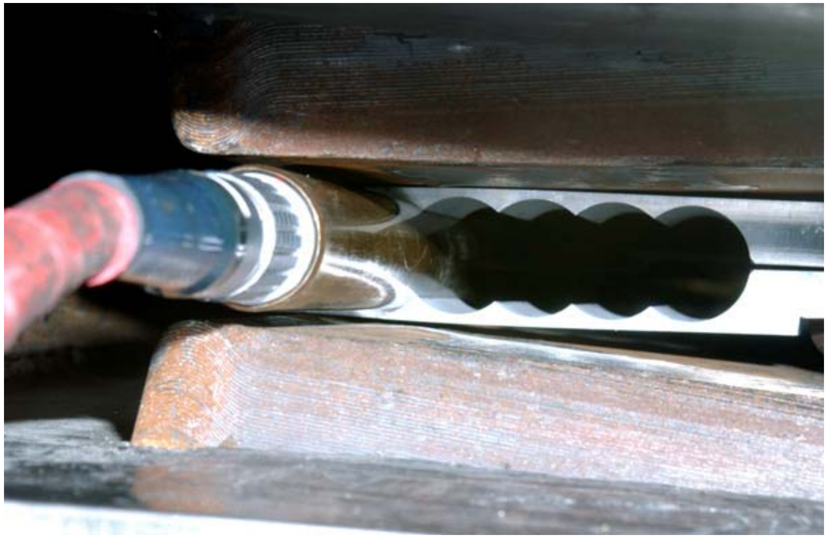
Booster Cell With 2nd Harmonic
(courtesy D. Wolff)



Booster Cell With 2nd Harmonic (cont…)

Field Measurement at E4R

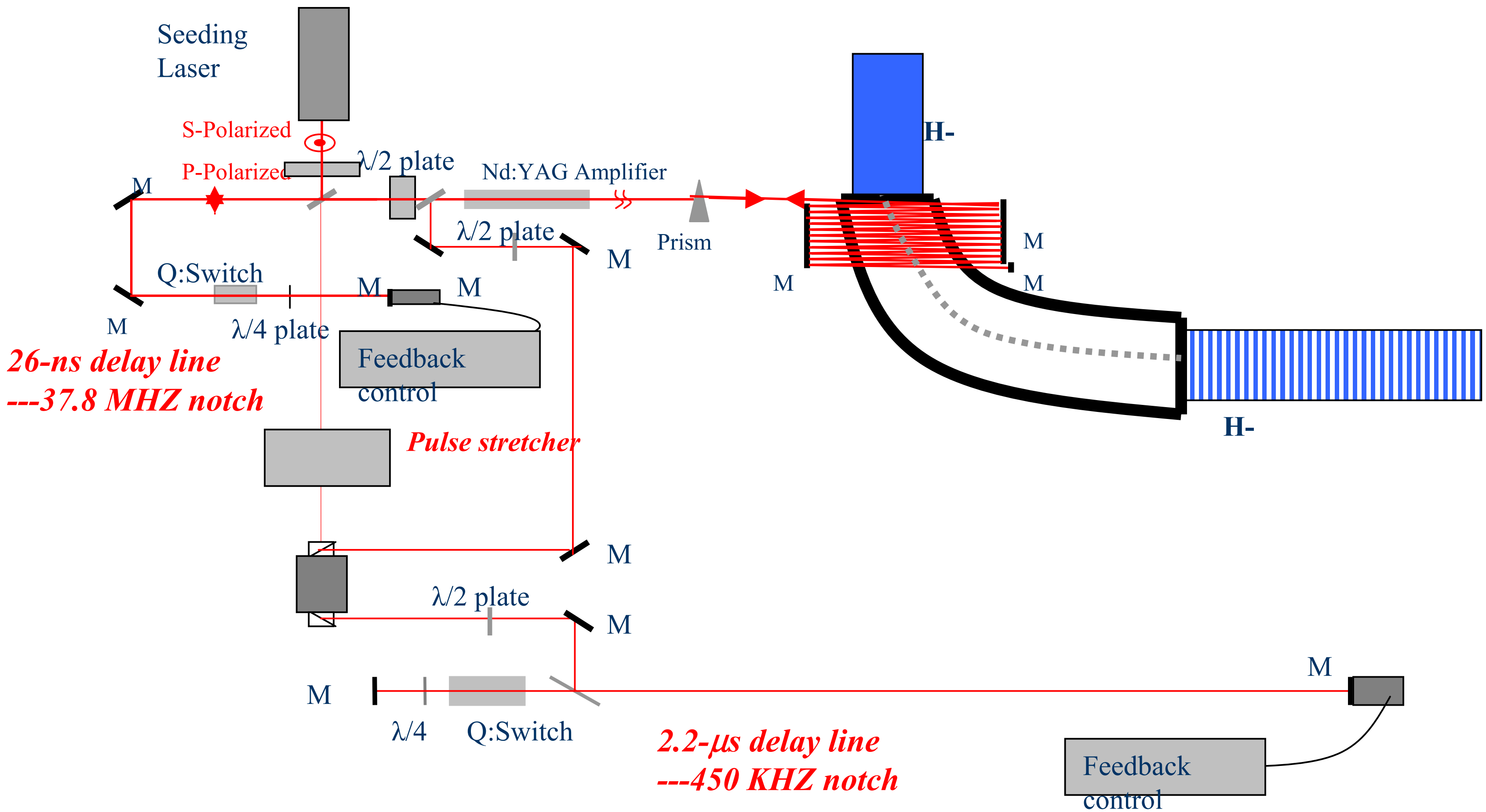
(courtesy J. DiMarco and P. Schlabach)



A mole used for field measurement

Laser Chopping

(courtesy R. Tomlin and X. Yang)



Superconducting Dipole Magnet (courtesy V. Kashikhin)

Main Issue:

Superconducting cable and winding with low eddy current losses

Magnet Parameters:

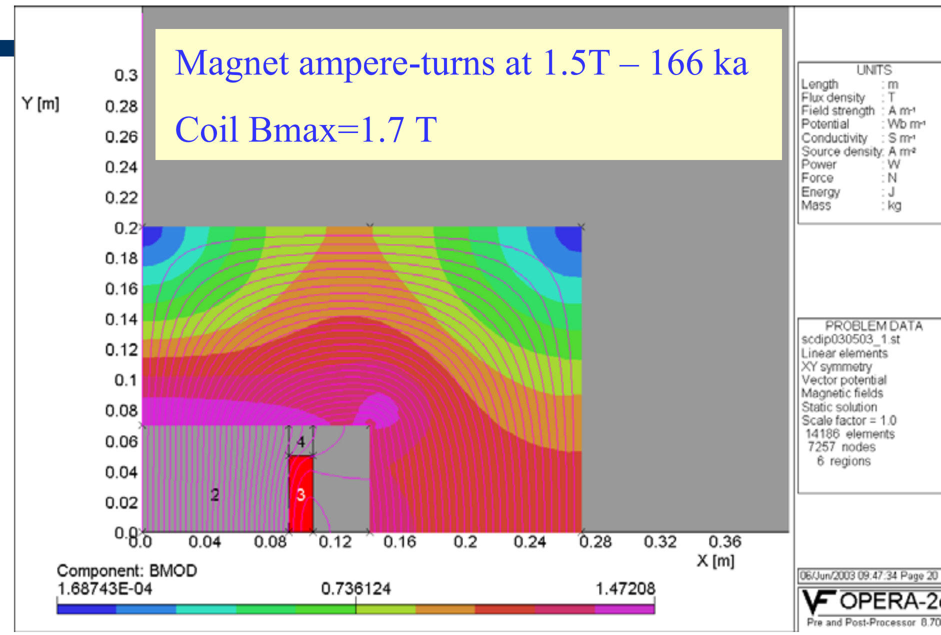
Magnetic field	**1.5 – 3.0 T**
Frequency	**15 Hz**
Air gap	**100 – 150 mm**
Length	**5.72m – 2.86 m**
Superconductor	**NbTi/CuNi or HTS**
Iron/air core	**room temperature**
Cooling	**LHe forced flow**

Superconductor AC losses < 3.3 kW/m^3 at 15 Hz and 0.5 mm dia.
Losses for 1.5 T magnet 1.2 W/m for NbTi/CuNi ALSTHOM superconductor with 0.16 um filaments

Hysteresis losses can be effectively reduced by decreasing a filament size up to ~ 0.2 um

Magnet ampere-turns at 1.5T – 166 ka

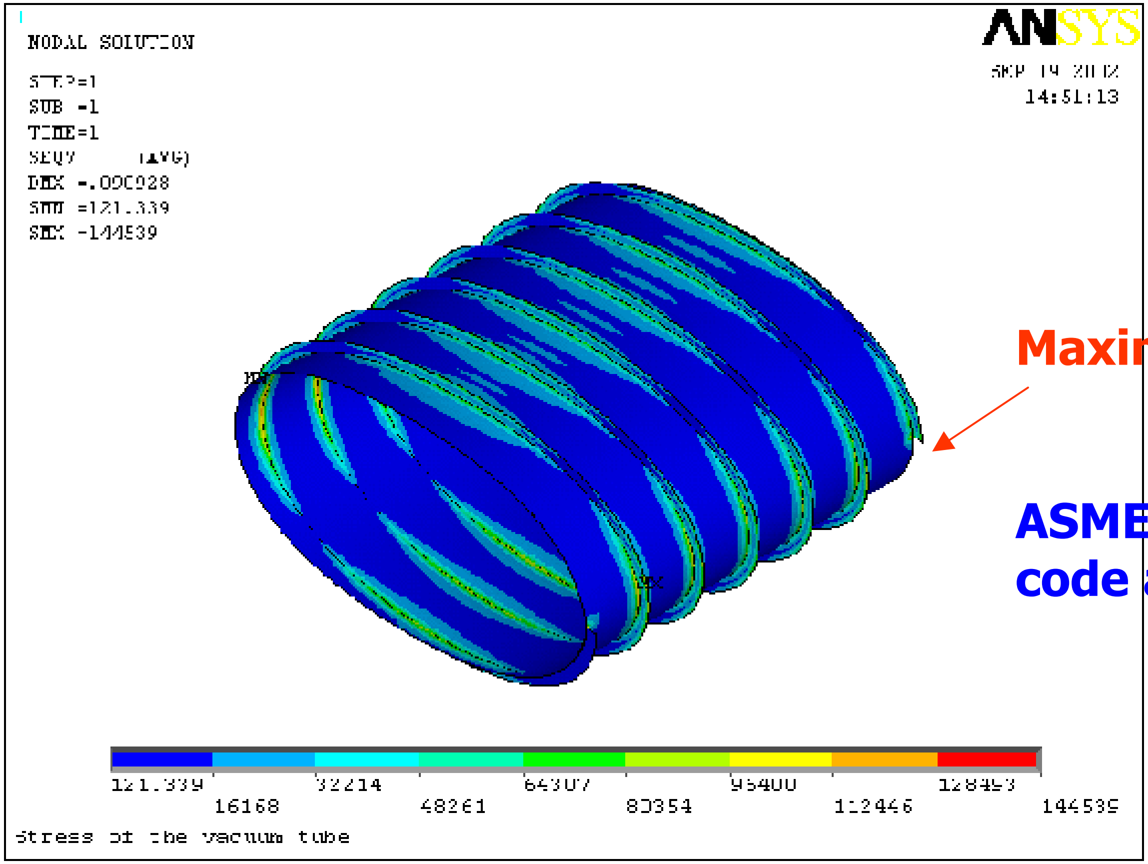
Coil Bmax=1.7 T



Eddy current losses effectively reduced by using high resistive CuNi matrix and small twist pitch 1.5mm for sub-wire and 6-8mm in 0.5mm wire.

Careful optimization needed between SC cable, cooling pipes/channels and construction elements to reduce heat load up to reasonable value

Beam Pipe Stress Analysis
(courtesy Z. Tang and A. Chen)



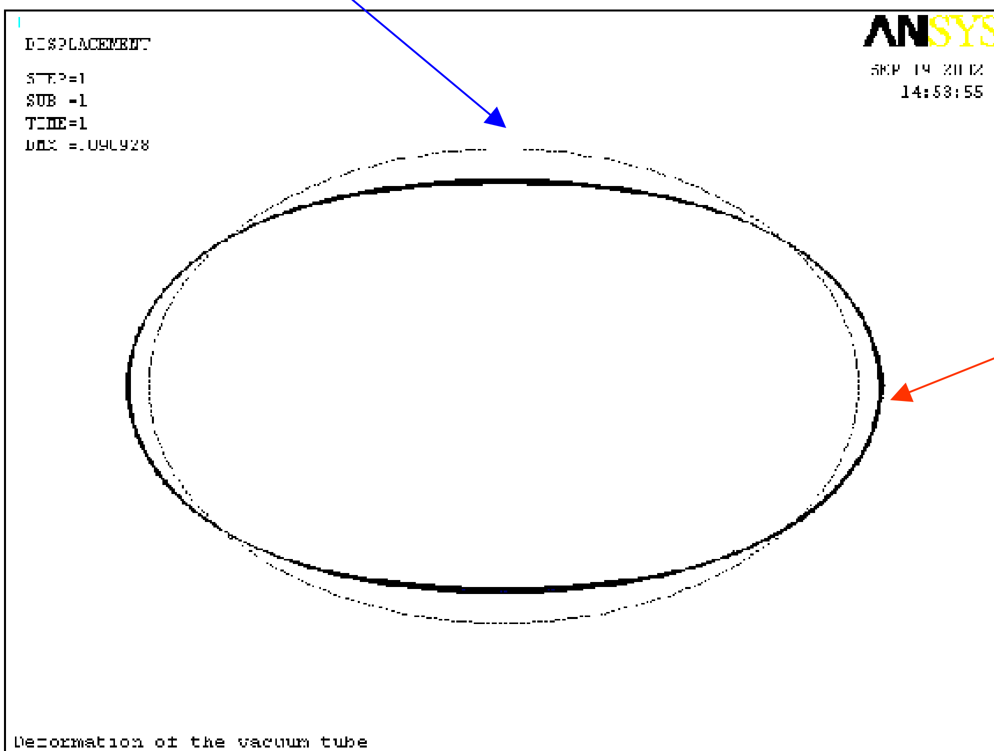
Maximum stress 130 ksi

ASME pressure vessel code allowance: 170 ksi

Beam Pipe Deformation Analysis

(courtesy Z. Tang and A. Chen)

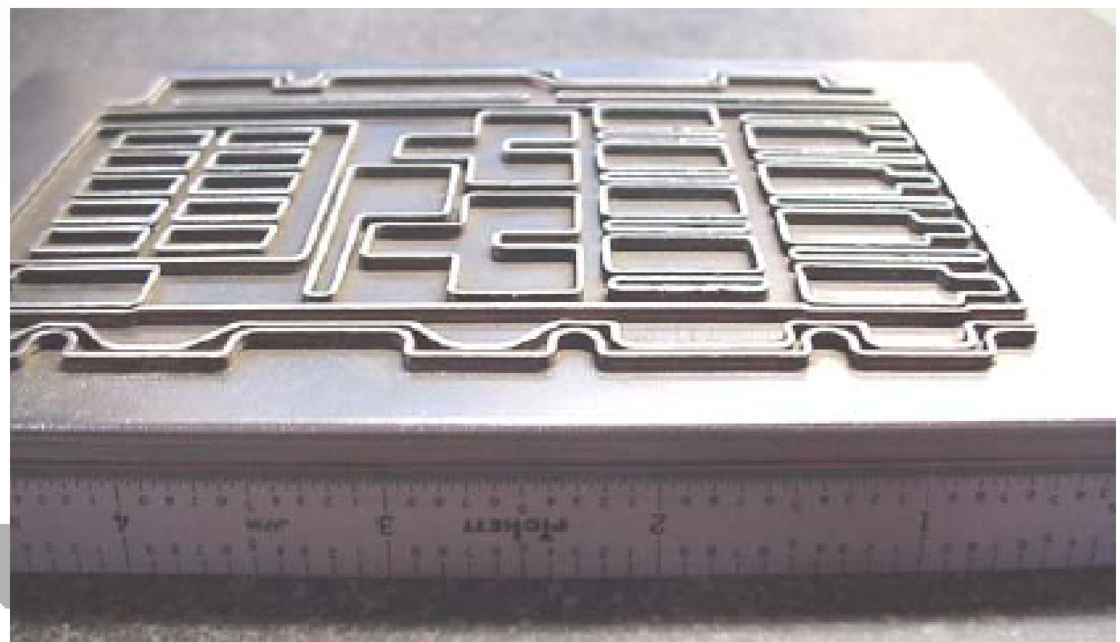
Max Δy = – 0.089 in



Max Δx = 0.055 in

Laser Precision Metal Deposition
(courtesy H&R Technology Inc.)

Cutting die prior to sharpening;
Die Base: Carbon Steel, Knife Pattern: 420 SST



R&D Cost Estimate (M/S Part)

Laser chopping	$38 k
Dual harmonic power supply test	$45 k
Thin metallic pipe	$60 k
Inductive inserts	$ 6 k
Magnet R&D	$60 k
AC sc magnet development	$50 k
Collimation system	$10 k (FESS)
RF modification	$0

Total: $269 k

Conclusions

- With a Proton Driver, Fermilab will get two high power proton facilities – the PD itself (0.5-2 MW), and a 2-MW Main Injector.
- This will put Fermilab in a solid leading position in the neutrino physics for a foreseeable future and also open up a wide field for a variety of physics programs.
- The construction cost is modest and can be supported by the HEP base program.
- It is *"the One"* that Fermilab has been seeking and can fit properly in the time window between the end of Run2 (2009) and a possible beginning of a linear collider (2015?).

Questions?